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SUMMARY

An experimental investigation was made to determine the effects of a vibration environment on the critical currents of superconducting magnets and to determine a method of obtaining reliable performance of the magnets when subjected to vibrations. The degradation of the critical currents of the magnets was investigated within a vibration range of 100 to 2000 hertz with magnet accelerations up to 440 g. Results are presented showing the dependence of the critical currents and the performance reliability on vibration for potted and unpotted magnets wound of seven-strand and single-strand niobium zirconium (NbZr) cable coils. Simple stiffening of the coils with a potting resin increased the critical current and performance reliability over that obtained from the unpotted magnet subjected to the same vibrations.

INTRODUCTION

Several observations have indicated that superconducting magnets are sensitive to vibration environments. It has been observed that the maximum current, or critical current, that a superconducting magnet can maintain while in a helium bath decreased when the magnet was subjected to mechanical vibrations (refs. 1 and 2). The current that a superconducting solenoid can maintain is determined by the magnetic field and temperature of the wire. The mechanisms which tend to increase the temperature of the wire are relative motion between wire turns of the solenoid, flapping of end plates, decay of eddy currents induced in the sheathing, and flux motion and jumps in the superconducting materials. When a section of the wire exceeds the temperature-field limitations, the material becomes normal with the normal front propagating throughout the magnet.

Krzycki, Byrne, and Lee (ref. 1) demonstrated that a charged superconducting magnet can be driven normal by rocket engine vibrations. An investigation of the effect of vibation on small coils known to have loose turns was made by Laverick (ref. 2) by striking them, by vibrating them at 40 hertz with accelerations of ±4 g, and by vibrating them at 20 000 hertz. Laverick concluded that, for the small coils subjected to vibrational stresses, the use of a binder or potting compound to stiffen the coils allowed operation at higher currents than coils wound without such treatment. However, data on superconducting characteristics was not available for superconducting magnets in a vibration environment at other frequencies and accelerations.

The two-fold purpose of this investigation was to determine the currents various superconducting solenoids could maintain when subjected to a vibration environment, and to determine methods of ensuring predictable performance of superconducting magnets subjected to vibration. The degradation of critical currents due to vibrations was investigated at driving frequencies within a range of 100 to 2000 hertz with magnet acceleration as high as 440 g's. Performance reliability and the dependence of critical current on vibrations was determined for unpotted magnets of niobium titanium (NbTi) and NbZr. Both a seven-strand and a single-strand NbZr coil were subsequently rewound, potted, and retested. All the magnets tested were wound on identical coil forms to produce a magnetic field of 0.05 to 0.07 tesla per strand-ampere.

SYMBOLS

H_c critical field

I_c critical current

I_s static critical current at 4.2° K

EXPERIMENTAL APPARATUS

The superconducting coils were subjected to the vibration environment by mounting them on a stainless-steel tube which was threaded into a shaker. The coil was in a liquid helium bath during the tests. A sketch of the Dewar, shaker, and test magnet in the test position is presented in figure 1. The shaker was capable of producing a 50-g acceleration at frequencies from 100 to 5000 hertz with a maximum displacement of 2.5 centimeters.

The tube and magnet assembly was underdamped while vibrating in the liquid helium bath. The resonant frequency was between 500 and 600 hertz for all solenoids tested since the same support tube was used for each and the masses of the solenoids were

approximately the same. The accelerations of the top and bottom spool flanges were monitored with piezoelectric accelerometers. A typical plot of the accelerometers' outputs as a function of frequency for the single-strand magnet is presented in figure 2. The top and bottom plates were not always in phase except around resonance.

The sensitivities of the accelerometers immersed in liquid helium were determined by comparing the output voltage to a calibrated accelerometer mounted on the driver that operated at room temperature. The assembly was operated at low frequencies, where it could be assumed the assembly acted as a rigid member (100 Hz). The outputs of the accelerometers mounted on the top and bottom flange were linear in the range tested, 0 to 50 g. Higher accelerations could not be obtained at the 100-hertz frequency. It was assumed that the output remained linear to the peak accelerations (440 g) reported. The sensitivities of the top and bottom accelerometers were 2.96 ± 0.15 and 2.15 ± 0.15 root-mean-square millivolts per peak Earth-gravity acceleration, respectively.

The superconducting magnets tested were wound on 3.8-centimeter-long stainless-steel coil spools that had an outside diameter of 7.6 centimeters and an inside diameter of 3.3 centimeters. The wire was wound to a diameter of 5.4 centimeters. The coils were wound on a coil winder with a manually applied tension of about 10 newtons. Each layer was secured with a 0.0013-centimeter-thick coating of mylar insulation. The unpotted coils tested were wound of various makes of 0.026-centimeter single-strand NbZr and NbTi wires as well as a seven-strand NbZr cable. Table I lists the characteristics of the wires tested.

To test the effect of stiffening on the magnet performance, the NbZr cable magnet and a single-strand NbZr magnet were rewound on the same coil forms by using the same

TABLE I. - DESIGN PARAMETERS FOR SUPERCONDUCTING COILS

[Cladding on radius, 0.0025-cm Cu.]

Source	Wire alloy	Conductor size outside diameter, cm	Insulation on radius		Turns	Magnetic field, T/strand-A
			Material	Thickness, cm		
A	NbTi	0.0254	Fused nylon	0.0025	3026 in 27 layers	----
A	Nb - 25 Zr				2958 in $26\frac{2}{3}$ layers	----
B	Nb - 25 Zr				2974 in 30 layers	0.07
B	Nb - 25 Zr (potted)				2894 in 30 layers	----
A	Nb - 25 Zr (seven-strand potted)	0.0254 (per strand)	Teflon tape	.015	294 in 10 layers	.05

coil winding procedures except that each layer was coated with 50-percent-by-weight clay-filled polyurethane potting resin. The tests were then repeated on these two coils.

The superconducting to normal contacts of the single-strand magnets were made with pressure contacts. The seven-strand superconducting to normal contacts were made by spot welding the NbZr to an aluminum foil and then embedding the foil in solder. The current leads were secured by potting for all magnets tested. A picture of the seven-strand cable coil with accelerometers attached is presented in figure 3.

TESTING PROCEDURE

The various coils were first evaluated statically in a liquid helium bath temperature of 4.2° K. Critical currents, that is, the superconducting to normal transition currents, were determined and were used as the reference current in the subsequent evaluation tests. Three types of vibration tests were made on each magnet. First, an indication of the current carrying capability of the magnets in a vibration environment was obtained by determining the highest current each maintained while subjected to a fixed 5-g driving acceleration and a frequency sweep from 100 to 2000 hertz. Second, information of critical current degradation due to vibrations was then obtained at a number of frequencies by setting the magnet current and then driving the magnet normal by increasing the driving force. The accelerometers outputs were recorded when the magnet was driven normal for a number of preset currents at each frequency. Finally, in order to isolate uncontrolled motion that might have been produced in the magnet during an increase of the driving force, the magnet was also driven normal by increasing the current while the magnet was subjected to a fixed driving force. The critical currents were recorded for each of a number of preset driving forces at fixed driving frequencies.

As will be discussed in the Resin-Potted Single-Strand Magnet section, the potted coils were stable except at very high accelerations; therefore, accelerations required to drive the single-strand potted coil normal could only be obtained in a frequency range of 200 hertz around the resonant frequency.

RESULTS AND DISCUSSION

Unpotted Magnets

The highest transport current that the magnet maintained while subjected to the acceleration represented in figure 2 was one of the performance characteristics determined. The unpotted magnets, which had critical currents ranging from 21 to 45 amperes

when stationary at 4.2° K, did not maintain more than 5 amperes while subjected to a fixed magnitude driving acceleration and a sweep of the frequency range which resulted in the local accelerations illustrated in figure 2.

In order to minimize the effect of flange motion, one NbZr magnet subsequently had its coil form reinforced with stainless-steel posts. It then had unpredictable critical currents ranging from 5 to 40 amperes when subjected to the vibration tests. Only one of the magnets tested had a change in its stationary critical current after it was subjected to a number of 5-g driver tests. The NbTi magnet, which was wound and tested twice, degraded such that the critical current while stationary decreased from 21 to 8 amperes the first time it was wound and from 19 to 3 amperes the second time it was wound.

The critical points determined for the unpotted coils at a fixed driving frequency were not reproducible. Although it was not possible to predict or reproduce the performance of unpotted magnets, their critical currents were in general much lower than those of a potted coil subjected to the same vibrations. It was observed that the unpotted coils performed better the second consecutive day of testing when water vapor could have condensed and formed ice which in effect potted the magnets.

Resin-Potted Single-Strand Magnet

The single-strand coil which had the highest critical current when not potted was subsequently rewound with a potting resin between layers. After potting, the stationary critical current was 44 to 50 amperes at 4.2° K. The measured field was 3.15 to 3.5 teslas. The critical current and self field of the magnet was within 3 amperes of the material's short sample I_c - H_c curve. When the magnet was subjected to a maximum 170-g acceleration during the frequency sweep at a 5-g driving acceleration, the magnet could maintain 40 amperes without going normal.

Since the potted magnet could not be driven normal at obtainable accelerations with currents less than 40 amperes at frequencies above 725 hertz or below 450 hertz, the critical current data points obtained were limited to the frequency range of 500 to 700 hertz. The critical current data points obtained for the potted single-strand magnet by increasing the driving acceleration while maintaining a fixed magnet current and driving frequency were not different from those obtained by increasing the current at a fixed driving acceleration and frequency. This indicates that the time rate of change of the acceleration did not influence the environment of the superconductor much differently than the time rate of change of current.

The data points obtained with the single-strand magnet were within the two bands presented in figure 4, which is a plot of the reduced critical current as a function of the maximum accelerations of the top and bottom plates measured when the magnet went

normal. The test results on the unpotted magnet (with post supports) of the same material obtained at the single frequency of 500 hertz have also been presented in figure 4 for comparison. The reduced critical current was obtained by dividing the critical current with vibration by the average critical current with no vibration: this was 42.5 amperes for the unpotted magnet and 47.5 amperes for the potted magnet.

The variation in the normalized critical current with acceleration of either the top or bottom flange was linear for any particular set of data points obtained for a given frequency. The difference between the top and bottom accelerometer readings increased as the critical current decreased. The difference is also illustrated by the bracketing lines in figures 4 and 5. The correlation between the reduced critical current and difference in accelerations suggests that the accelerometer difference is related to energy input into the coil. Unfortunately, the coupling between the coil end plates and each turn cannot be determined. The intersection of the two bands with $I_c/I_s = 1$ is probably determined by the rate at which the absorbed energy can be given to the helium bath without increasing the local wire temperature above its critical values. There was no trend established by the data points which was dependent on frequency. The day to day variations and inaccuracies in acceleration determination were greater than any noticeable frequency dependence.

Resin-Potted Seven-Strand Solenoid

The potted seven-strand coil had a critical current of 225 to 238 amperes at 4.2° K. The highest current the magnet maintained while subjected to the frequency sweep at a 5-g driving acceleration was 220 amperes. The maximum acceleration the magnet was subjected to during the frequency sweep was 70 g, which occurred at the resonant frequency of 510 hertz.

The critical current data obtained for various driving accelerations at a fixed frequency were limited to a driving frequency range of 450 to 650 hertz. The critical current data points for the potted seven-strand coil varied more than those of the potted single-strand coil. The results of one day could not be repeated on other days. The critical values obtained by increasing the current at a fixed driving acceleration and frequency were generally lower than those obtained by increasing the acceleration at a fixed current and frequency. The data points for the seven-strand potted solenoid were within the two bands presented in figure 5.

CONCLUDING REMARKS

Superconducting magnets immersed in liquid helium were driven normal at currents less than their 4.2° K critical currents by subjecting the magnet to vibrations. This investigation revealed that simple stiffening of the coil by a potting resin increased the critical current considerably over the critical value obtained for the unpotted coil subjected to the same vibrations. Of the two potted coils tested, the single-strand coil had fairly predictable critical currents, whereas the seven-strand coil did not. The potted single-strand coil maintained at least 84 percent of its stationary critical current when subjected to a vibration up to a 170-g acceleration in a frequency range up to 700 hertz and could not be driven normal at currents less than 84 percent of the 4.2° K value from 700 to 2000 hertz at the obtainable accelerations.

The results of this investigation, which was conducted with a power supply attached, should be similar to those obtained with coils in a persistent current state. The newly available stabilized superconducting material may produce magnets less sensitive to vibrations. Indeed, winding techniques that are necessarily involved in the construction of successful large field, large volume superconducting magnets could also result in magnets less sensitive to mechanical vibrations.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 9, 1967,
129-02-05-11-22.

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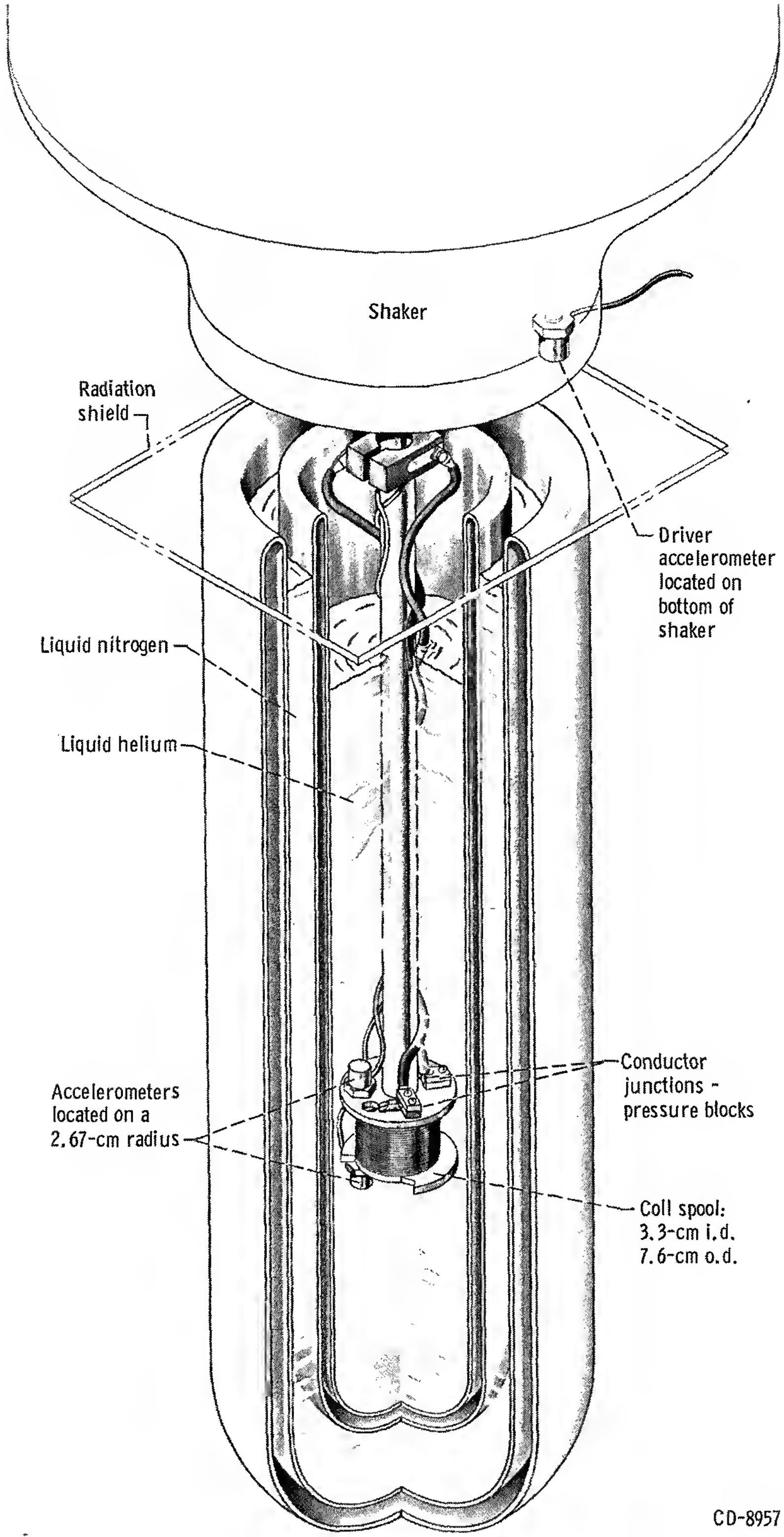

Figure 1. - Equipment.

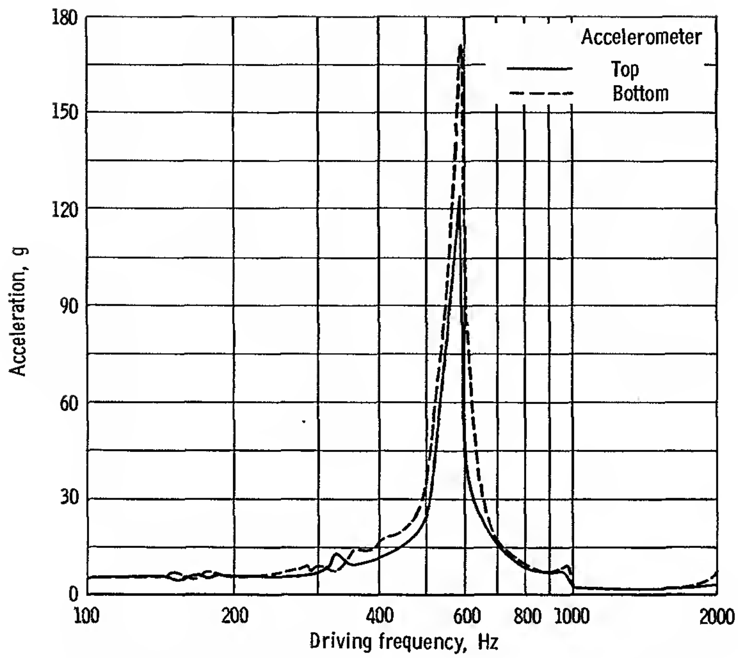

Figure 2. - Accelerometer outputs as function of driving frequency for a 5-g driving acceleration.

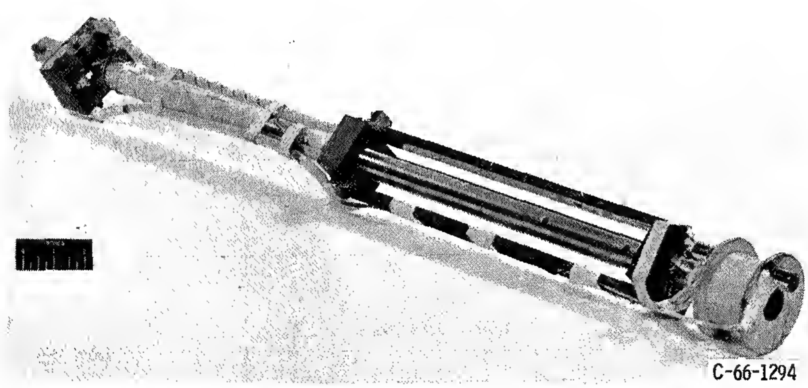

Figure 3. - Mounted superconducting coil.

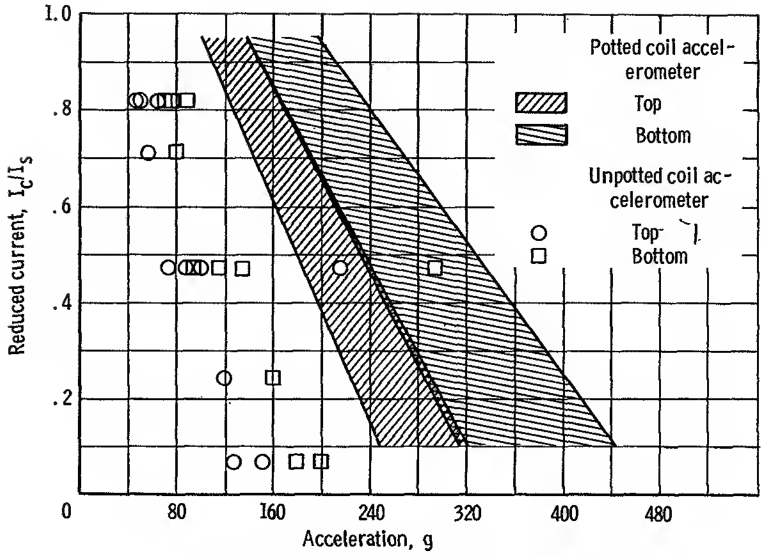

Figure 4. - Single-strand niobium zirconium solenoid.

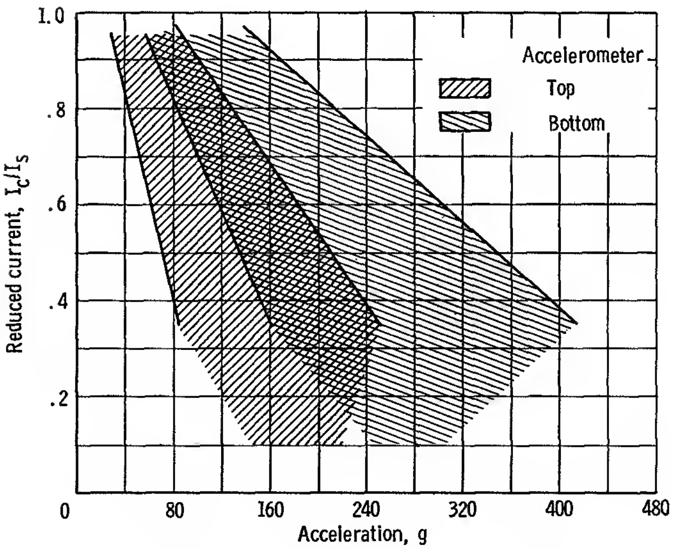

Figure 5. - Seven-strand resin-potted solenoid.

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